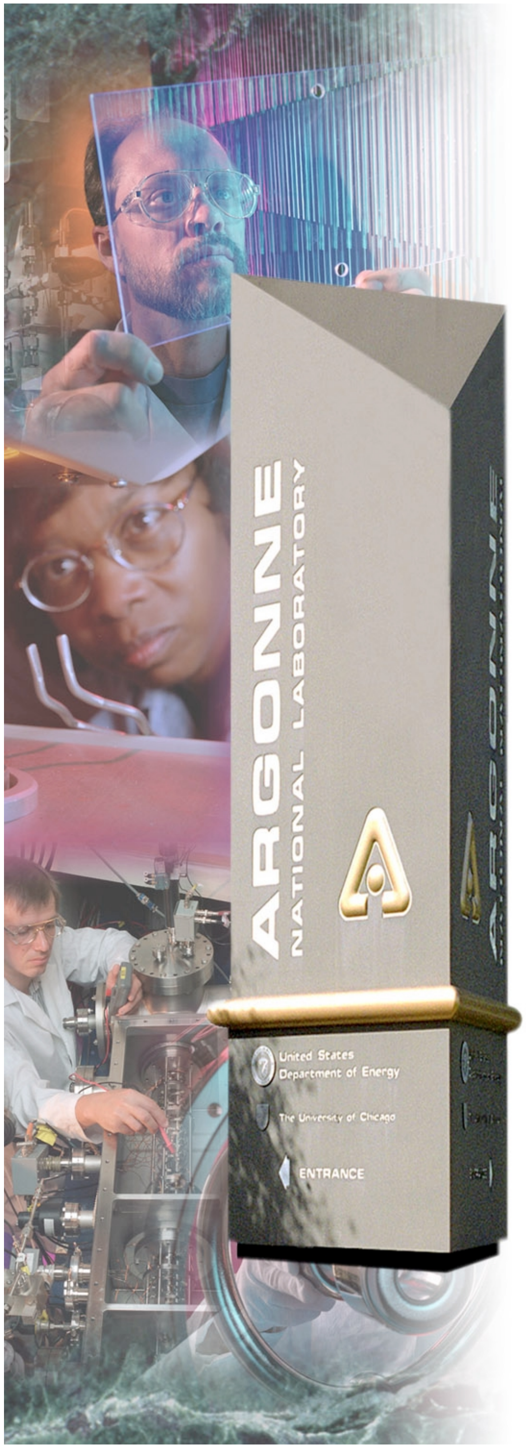

Dynamic Analysis of Nuclear Energy System Strategies for Electricity and Hydrogen Production in the USA

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Operated by The University of Chicago

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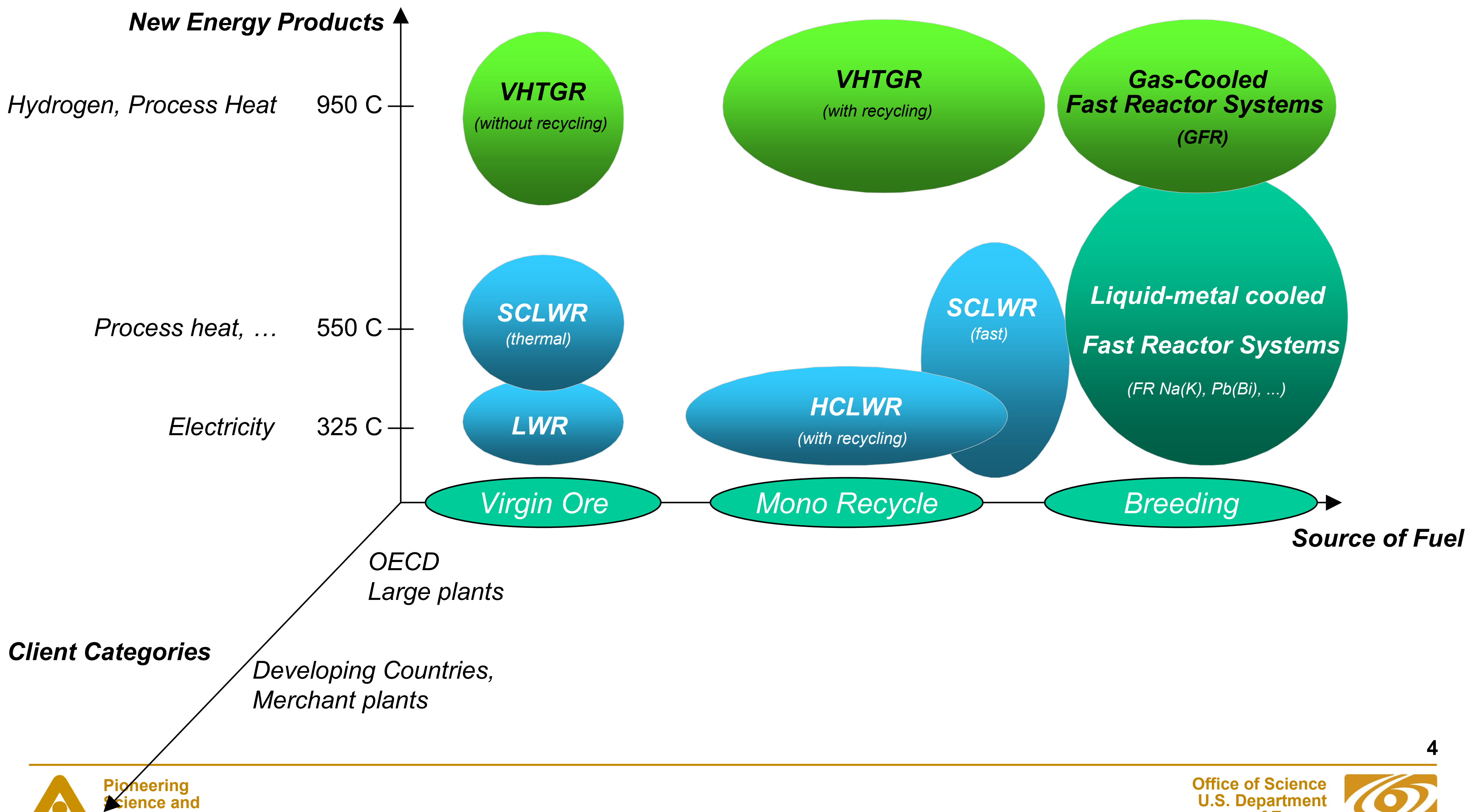
Background of this analysis

- Gen-IV identified 6 promising reactor concepts to serve the future energy market and also recognized the importance of closing the fuel cycle
- US Energy policy also favors the hydrogen economy and the first priority development effort of Gen-V in the US is a VHTR for H_2-production
- AFCI focuses on appropriate paths forward to close the fuel cycle taking into account the timing, technological, economic and institutional constraints

- The main question for this preliminary dynamic analysis becomes:
  - *What mix of reactor types and fuel cycle options are best suited to meet the projected demands of electricity and hydrogen production?*

Evolving Role for Nuclear Energy



Systems optimization question becomes …

- **How to allocate the fissile materials to reactor types to maximize the economic value added for the nuclear energy system as a whole, i.e. distribute the economic resource to reactor and fuel types according to their realizable contribution to this added value.**

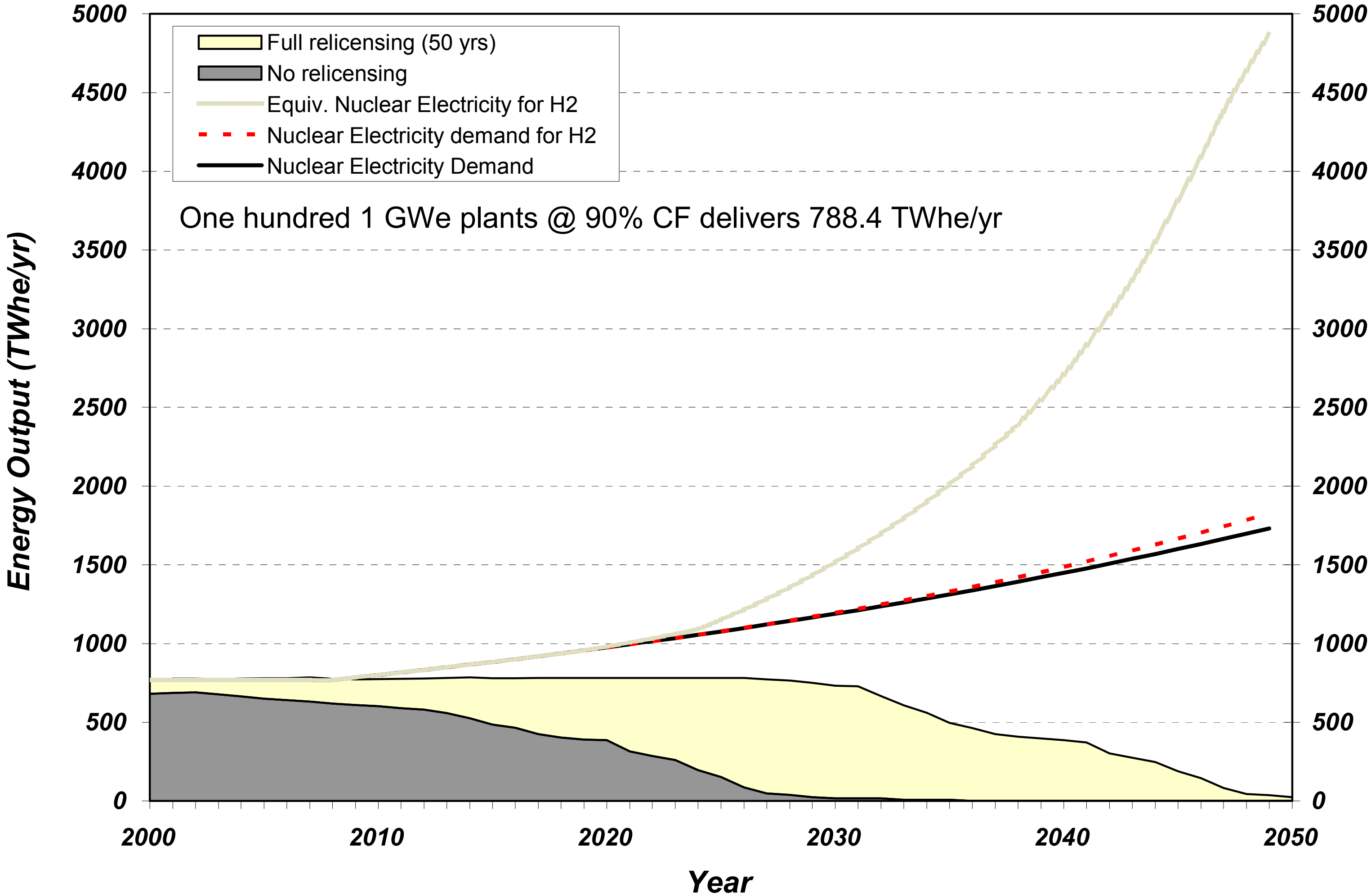
  - The planning horizon over which this economic value added is to be optimized is 40-60 years, i.e. lifetime of assets.

  - Used to inform government’s intervention to guide allocation through indirect tools, i.e. regulation, taxes, FOAK financing, …

Electricity and Hydrogen demand scenario for the US

- **Based on DOE/EIA & IIASA/WEC data,**
  - Overall electricity demand
    - 2000-2020, growth by 1.9 %/yr
    - 2020-…., growth by 1.4%/yr
  - *Energy demand assigned to nuclear is expected to grow by 2 %/yr after 2010*
  - Overall hydrogen demand
    - 2000-2020, growth by 2.2 %/yr
    - 2020-…., growth by 1 to 1.6 %/yr depending on sector
      - 1 %/yr residential and transport sector
      - 1.6 %/yr refinery sector
      - 1.4 %/yr commercial sector
      - 1.5 %/yr industrial sector
  - *Nuclear hydrogen production assumed from 0% in 2020 to 25% by 2050*

Total Nuclear Energy Demand



Four fuel cycle scenarios considered

- LWRs in once-through mode
- LWRs + HTGRs in once-through mode
- LWRs + FRs CR>1
- LWRs + HTGRs + FRs (different CRs)

- LWRs essentially for electricity production
- HTGRs + FRs for hydrogen production

Reactor and Fuel Attributes

Reactors	**PWR**	**BWR**	**ALWR**		**HTGR**	**FR**		
Thermal Power (MW_{th})	2647	2647	2647		600	843		
Electric Power (MW_e)	900	900	900		284	320		
Thermal Efficiency (%)	34	34	34		47	38		
Capacity Factor (%)	90	90	90		90	85		
Technical lifetime (yr)	50	50	50		50	50		
						CR		
Fuels						0.25	0.5	1.25*
	UOX	**UOX**	**UOX**	**MOX**	**Particle**	**Metal**		
Average Burnup (GWd/tHM)	50	40	50	50	120	200	120	22
# fuel batches	5	5	5		3	7	7	3
Cycle length (mo)	12	12	12		12	12	12	12
Initial U (t/tIHM)	1	1	1	0	1	0	0	0
Initial enrichment (%)	4.2	3.7	4.2	0.25	15.5	0.25		
Initial DU (t/tIHM)	0	0	0	0.91903	0	0.0395	0.061	0
Initial REPU (t/tIHM)	0	0	0	0	0	0.3305	0.5936	0.9253
Initial Pu (t/tIHM)	0	0	0	0.08097	0	0.519	0.2919	0.0651
Initial MA (t/tIHM)	0	0	0	0	0	0.1117	0.0535	0.0009
Spent U (t/tIHM)	0.93545	0.94576	0.93545	0.88753	0.85917	0.3305	0.5936	0.8965
Spent enrichment (%)	0.82	0.8	0.82	0.15	4.8			
Spent Pu (t/tIHM)	0.012	0.1085	0.012	0.05512	0.01883	0.3769	0.2365	0.072
Spent MA (t/tIHM)	0.00125	0.00114	0.00125	0.0074	0.002	0.0897	0.0452	0.0077
Spent FP (t/tIHM)	0.0513	0.04225	0.0513	0.04996	0.12	0.2029	0.1248	0.0238

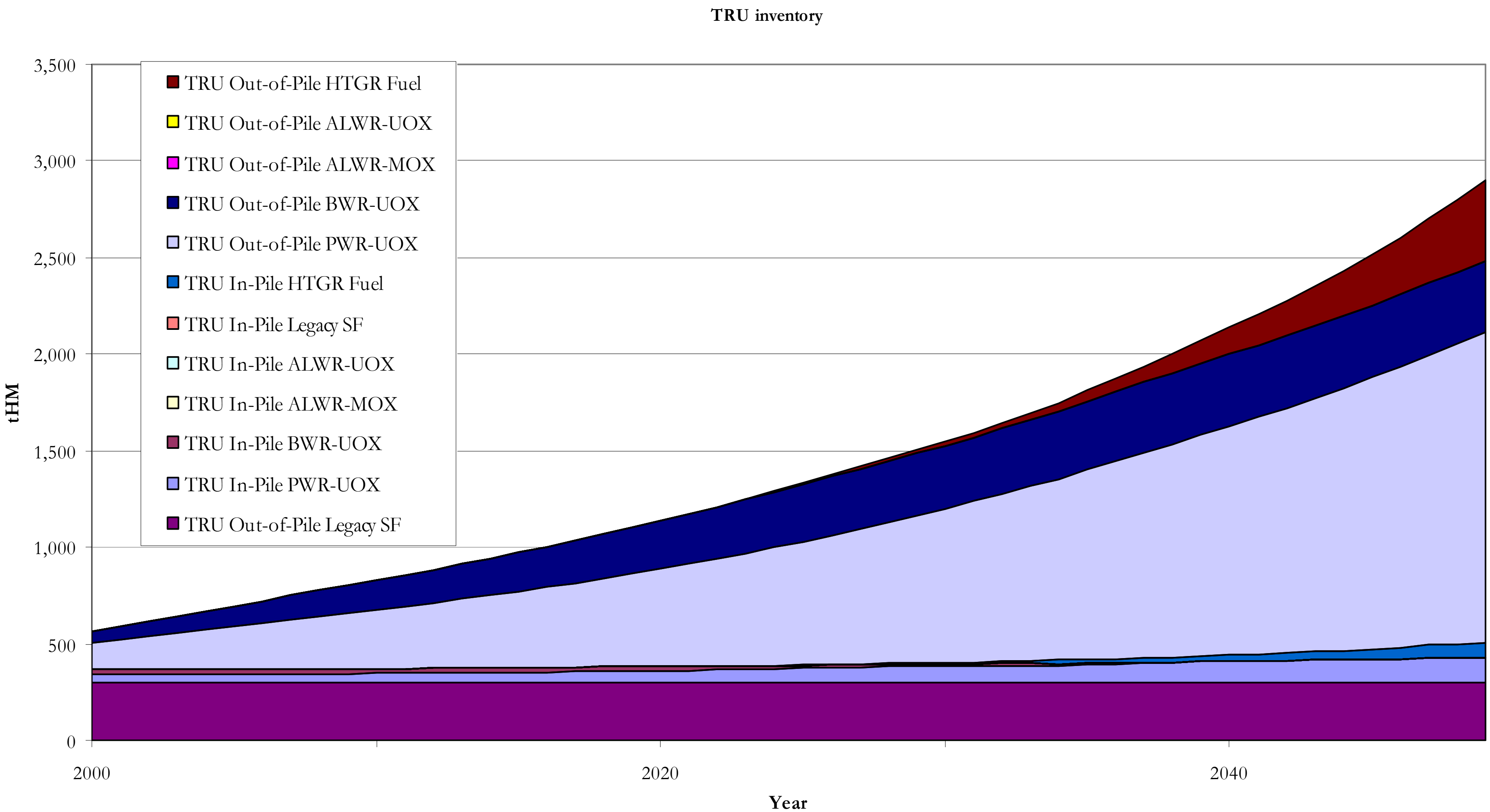
LWRs + HTGRs once-through operation

- **LWRs once-through operation for electricity demand only**
  - By mid-century
    - *190 000 tHM SF*
      - 2 400 tHM TRUs, including 2 180 tHM Pu
      - 1.5 million tons U_{nat} used during period of 2000-2050
        - On world-scale, this would become 5.9 million tU_{nat}
  - If also hydrogen energy demand should be delivered
    - *250 000 tHM SF, + 1 million tU_{nat} to be used*
- **LWRs + HTGRs once-through operation for electricity + hydrogen demand**

But rapidly growing HTGR SF stock and enrichment services by end of century

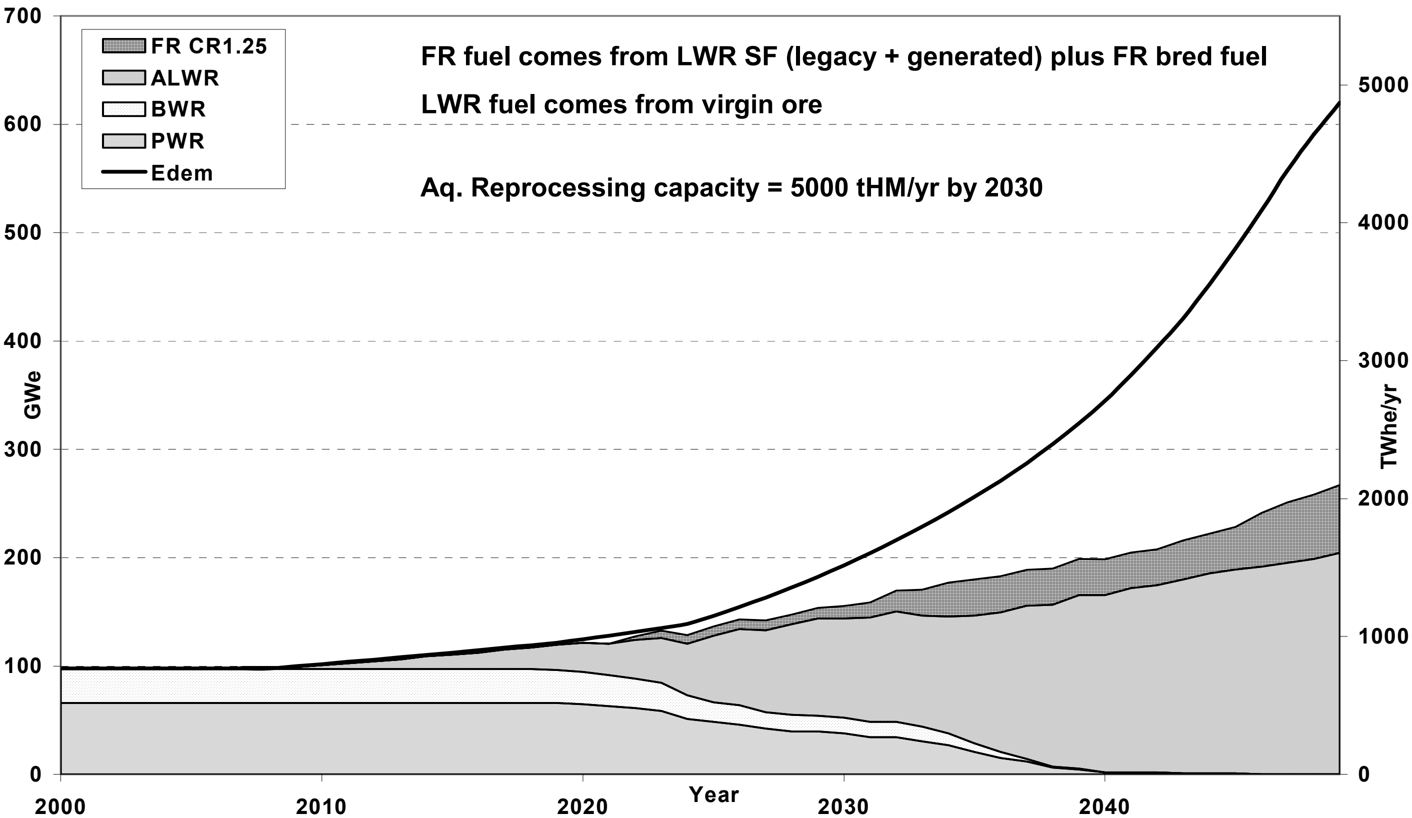
	ALWR	ALWR + HTGR
Energy demand	*Electricity*	*Electricity + hydrogen*
U_{nat} used 2000-2050 (10^6 tHM)	1.5	2.85
DU stock (10^6 tHM)	1.95	3.05
Enrichment (tSWU/yr)	31 200	152 400
Fabrication		
UOX (tHM/yr)	5 150	5 150
HTGR (tHM/yr)	-	3 500
SF at-reactor storage (tHM)	20 100	27 200
SF Interim storage (tHM)	171 200	174 500

TRU Inventory In-Pile and Out-of-Pile



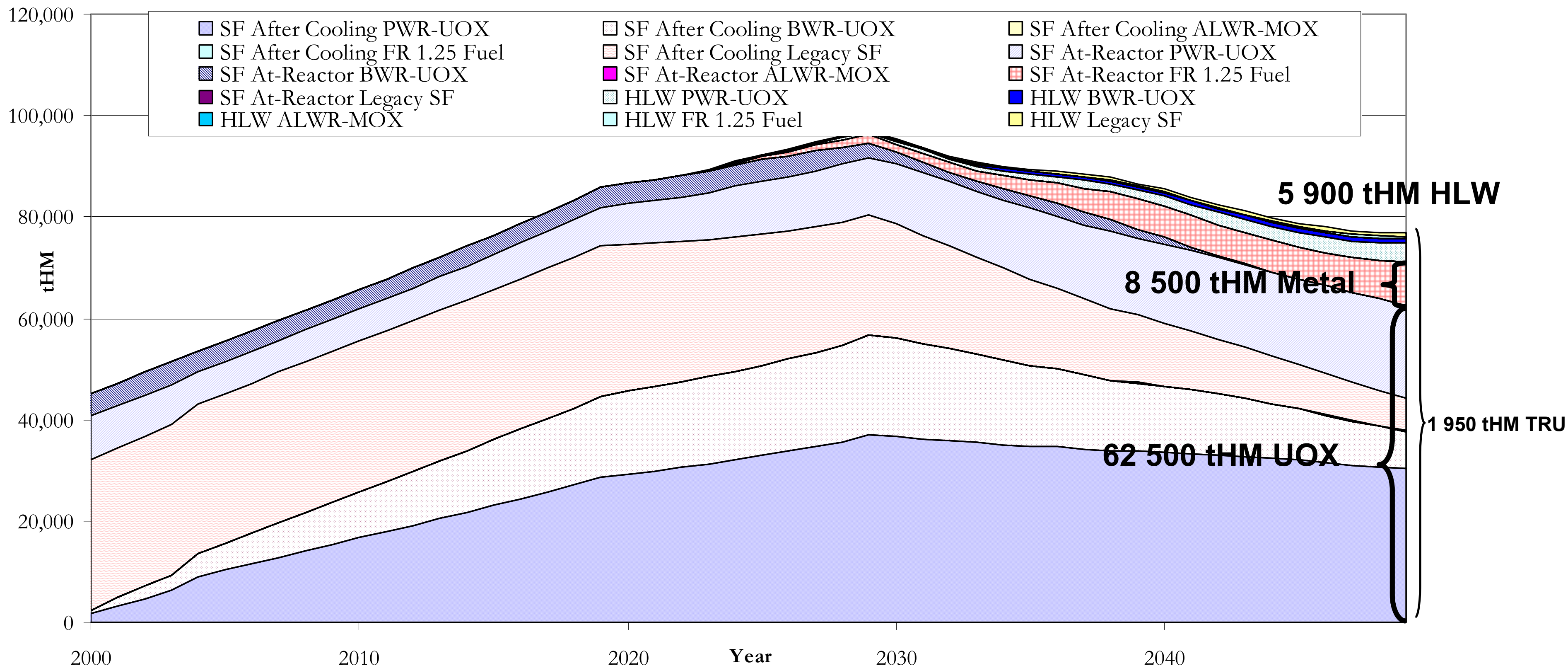
LWRs + FRs scenario

- **Starting from today's existing LWR-park, and assuming CR = 1.25 for FRs, what is the maximum amount of energy that can be produced assuming LWRs for electricity use and FRs for hydrogen production?**



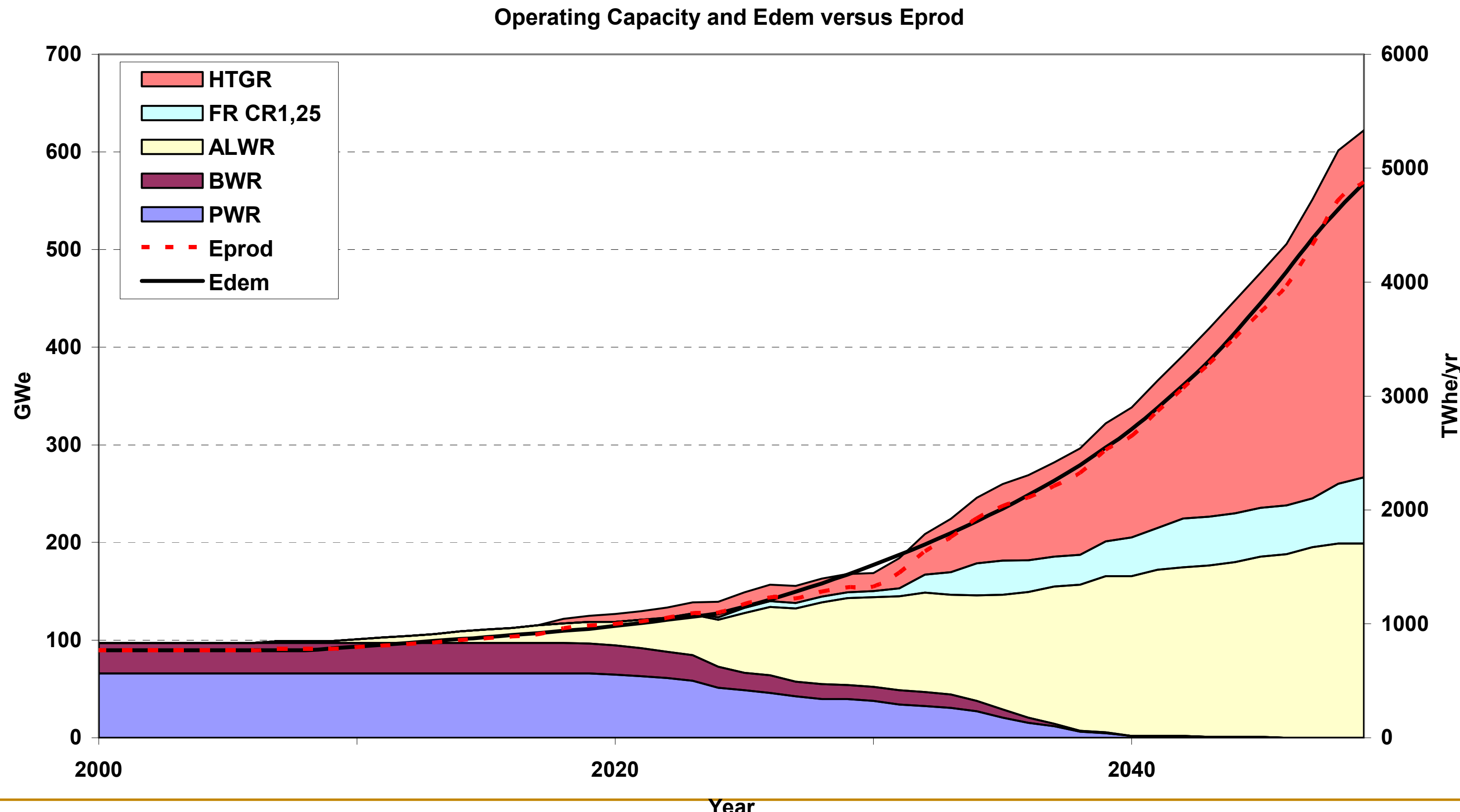
SF and TRU arising for LWRs + FRs scenario

- **LWR UOX Aq. Reprocessing:**
  - **2000 tHM/yr in 2020, + 3000 tHM/yr in 2030**
  - **5 year cooling time**
- **FR Metal Fuel Dry Reprocessing:**
  - **Up to 1 200 tHM/yr**
  - **5 year cooling time**

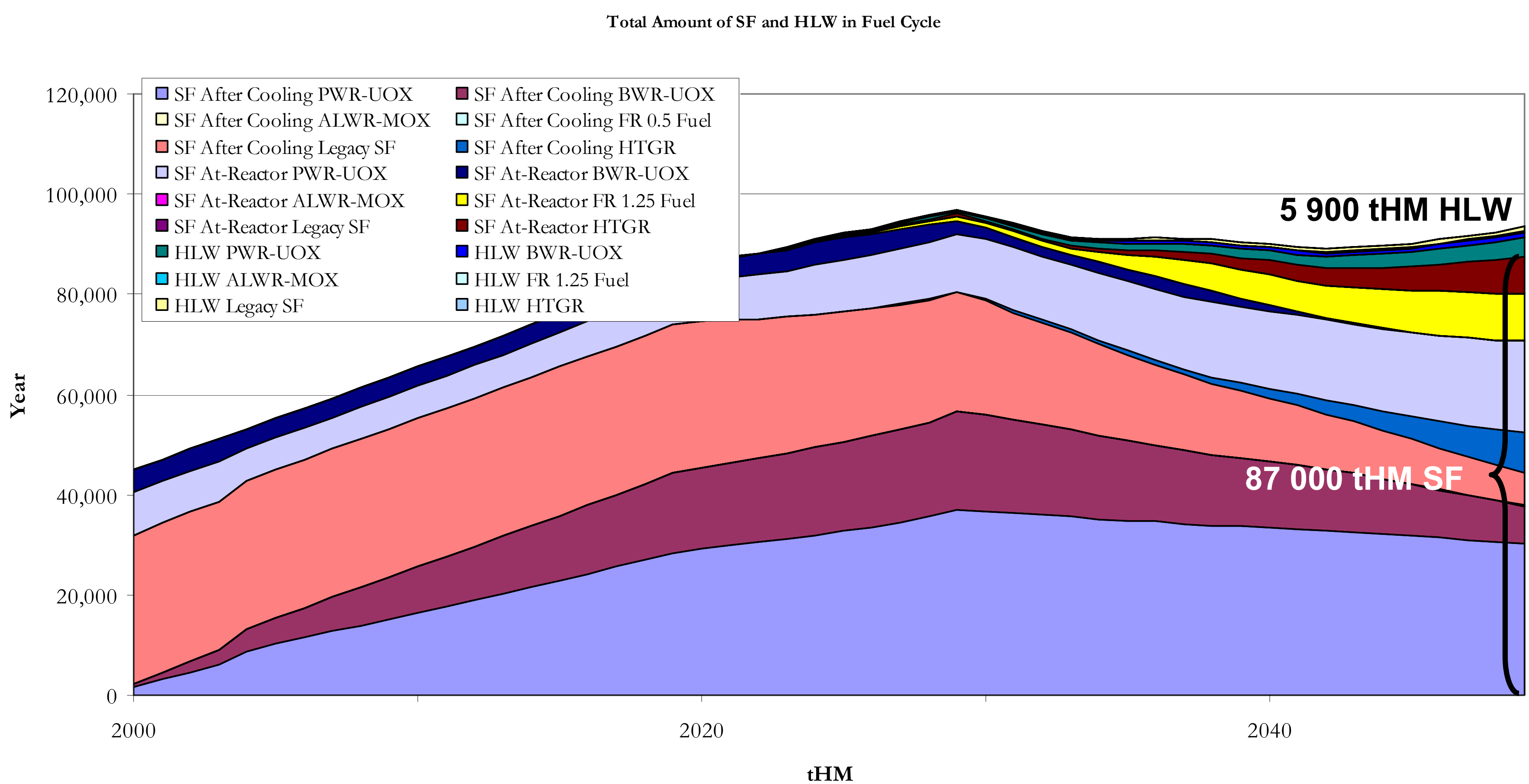


LWRs + HTGRs + FRs scenario

- **LWRs for electricity production**
- **HTGRs + FRs (different CRs) for hydrogen production**

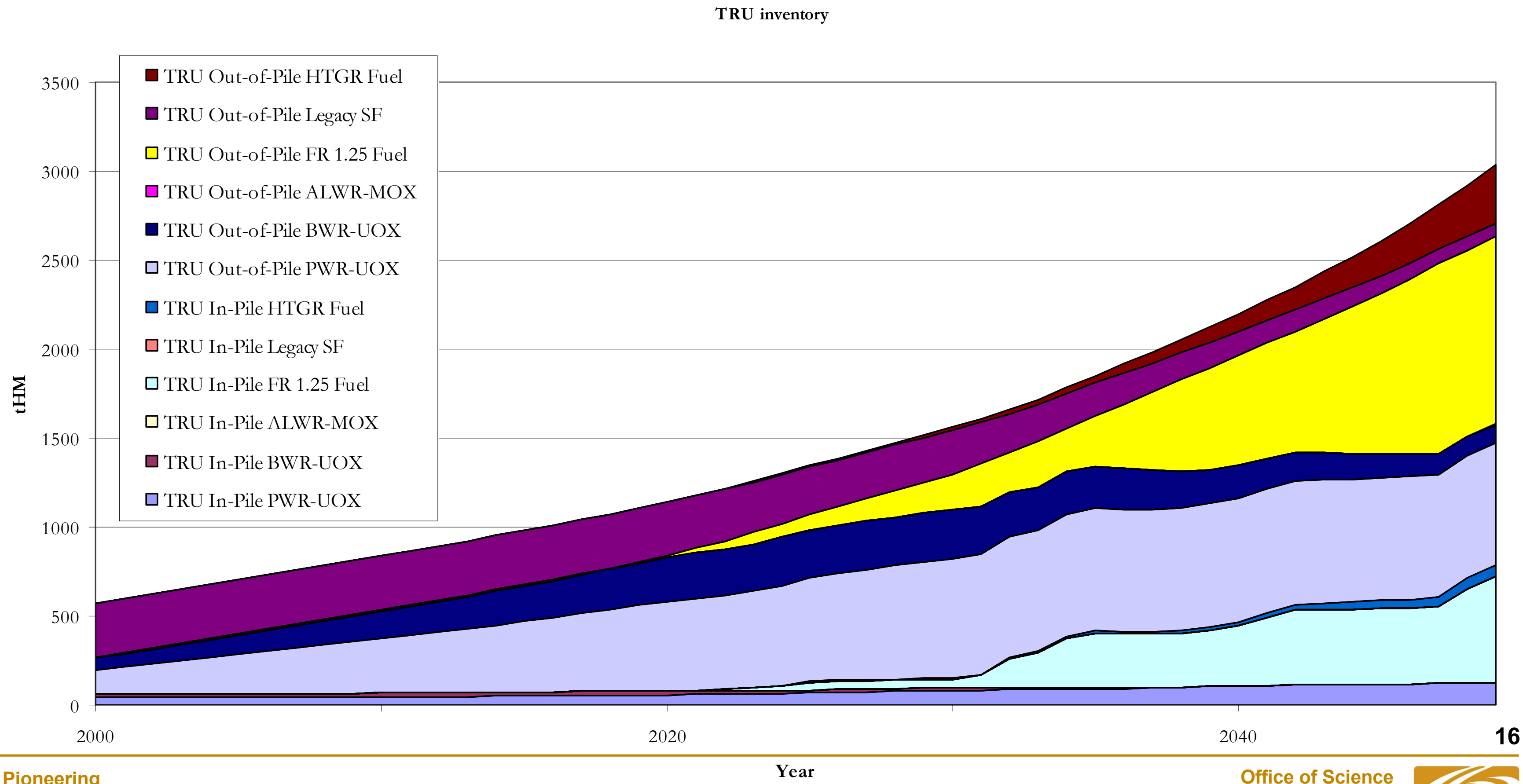


SF & HLW Inventory



TRU Inventory

- **In 2050**
  - CR = 1.25 TRU-amount = 2 250 tHM, 80 000 tHM SF
  - CR = 0.25 TRU-amount = 1 820 tHM, 88 000 tHM SF



Summary

- **A mix of**
  - 33 % LWRs once-through for electricity
  - 56 % HTGRs one-through for electricity/hydrogen
  - 11 % FR (CR 1.25) closed cycle for hydrogen

- **Succeeds to**
  - Meet demand for electricity and for hydrogen
  - Cap the SF stock at less than 100 000 tHM until 2050

- **But is it economic?**

Economics

- **Capital costs**
  - LWR 25.6 $/MWhe, i.e. 1 500 $/kWe overnight cost
  - HTGR 20.5 $/MWhe, i.e. 1 150 $/kWe
  - FR 37.7 $/MWhe, i.e. 2 000 $/kWe
  - WACC = 12 %, 17 years economic lifetime
- **O&M Costs**
  - 15 $/MWhe for all reactors
- **Fuel cycle costs**
  - HTGR particle fuel fabrication = 700 $/kgHM
  - LWR repro costs = 800 $/kgHM
  - FR repro costs = 1 100 $/kgHM; refab costs = 1 500 $/kgHM

$/MWhe	(A)LWR	(A)LWR + HTGR	(A)LWR + HTGR + FR CR 1.25
	Electricity	Electricity + hydrogen	Electricity + hydrogen + waste mgt
2020	50.1	49.9	55.3
2050	49.9	46.9	55.8

Conclusions

- **Preliminary dynamic analysis showed:**
  - Electricity + hydrogen energy demand can be met by nuclear energy
    - *But, LWRs + FRs based scenario may be limited and need additional HTGRs to match fast growing energy demands*
    - *However, HTGR SF stock is growing rapidly and important front-end needs*
  - If waste management considerations are taken into account, then LWRs + HTGRs + FRs scenario allows to:
    - *Keep SF amount in fuel cycle below YM (technical) capacity to 2050*
    - *Reduce TRU inventory in fuel cycle by at least 20 % (mid century)*
    - *Keep energy cost increase less than 10 %*